Carbon Sequestration in Terrestrial Ecosystems: A Status Report on R&D Progress

Gary K. Jacobs (jacobsgk@ornl.gov, 865-576-0567)
Oak Ridge National Laboratory
PO Box 2008, MS-6035
Oak Ridge, TN 37831

Roger C. Dahlman (roger.dahlman@science.doe.gov, 301-903-4951)
Office of Science/Biological and Environmental Research
U. S. Department of Energy
19901 Germantown Road
Germantown, MD 20874-1290

F. Blaine Metting, Jr. (blaine.metting@pnl.gov, 509-375-2607)
Pacific Northwest National Laboratory
902 Battelle Blvd.
PO Box 999, P7-54
Richland, WA 99352

Introduction

Sequestration of carbon in terrestrial ecosystems is a low-cost option that may be available in the near-term to mitigate increasing atmospheric CO_2 concentrations, while providing additional benefits. Storing carbon in terrestrial ecosystems can be achieved through maintenance of standing aboveground biomass, utilization of aboveground biomass in long-lived products, or protection of carbon (organic and inorganic) compounds present in soils. There are potential co-benefits from efforts to sequester carbon in terrestrial ecosystems. For example, long-lived valuable products (wood) are produced, erosion would be reduced, soil productivity could be improved through increased capacity to retain water and nutrients, and marginal lands could be improved and riparian ecosystems restored. Another unique feature of the terrestrial sequestration option is that it is the only option that is "reversible" should it become desirable or permissible. For example, forests that are created are thus investments which could be harvested should CO_2 emissions be reduced in other ways to acceptable levels 50-100 years from now.

The storage of carbon will occur at the local, or even molecular scale (in the case of soil carbon), but the actions to implement sequestration will have to be done at the regional scale. The need for a scientific basis for "energy-driven land management" (Jacobs and Graham, 2000)[1] is emerging as carbon management becomes increasingly important. Energy-driven land management includes both sequestration and its important relationship to the use of available

[1] Jacobs, G. K. and R. L. Graham, Carbon sequestration and bioenergy feedstock production seminar, Oak Ridge National Laboratory, Oak Ridge, TN, August 2000.

lands for the production of biomass energy feedstocks (for both fuel and power). These management strategies must be balanced against the important uses of lands for food and fiber production, other human needs, and options for preserving biodiversity. Thus, the consequences of sequestration actions must be assessed in an integrated manner.

The use of terrestrial ecosystems could be implemented globally with relatively small investment in new infrastructure right now. It is an option that is feasible and cost-effective in helping to mitigate increasing atmospheric CO_2 concentrations in the near term, while other lower-carbon energy resources or emission mitigation options are developed. Sharing of costs by multiple industry, government, and non-governmental organizations is another attractive option. In fact, projects are being implemented now in several countries. This approach of protection, management, and restoration of ecosystems could result in sequestration rates of perhaps 1-3 Gt C/y that could be maintained for several decades (DOE 2000)[2]. This quantity represents a substantial portion of current global emissions from land use change and fossil fuel combustion.

In addition to promoting practices known to benefit the storage of carbon in terrestrial ecosystems, there is potential to enhance this level of sequestration through investments in research and development. The increased potentials are difficult to estimate, but the range of estimates has been from 3-10 Gt C/y maintained for several decades (DOE 2000) [2]. These potentials are hypothetical and require R&D in several areas to become reality. Major questions that must be addressed are (1) What is the rate of sequestration that could be maintained, and (2) What is the maximum level of carbon storage in a terrestrial ecosystem that is possible or desirable? If the rate and capacity can be shifted, the next question is what are the impacts of these shifts and are they acceptable? Impacts can include energy costs to achieve sequestration, emissions of other greenhouse gases as a result of actions, changes in ecosystem structure and function, competition for land use, and more. This paper describes the current Carbon Sequestration Research Program of the U.S. Department of Energy's Office of Science – Biological and Environmental Research (BER) and how it is addressing these important questions.

Objectives

The goal of the BER research program is to provide science-based understanding to support the development and assessment of strategies for ***enhanced*** C sequestration in terrestrial ecosystems. The objective of the research is to have this understanding by 2025 so that new strategies (if deemed acceptable) could be implemented during the middle of this century that would increase global sequestration beyond the 1-3 Gt C/y that is considered feasible with current practices. Enhancing carbon sequestration in terrestrial ecosystems beyond normal management practices requires research in four areas (DOE 2000) [2]:

(1) **Understanding**: Can the rates and capacities of carbon storage in ecosystems be shifted? If so, how much?
(2) **Measurement**: How can carbon sequestration be detected at regional, local, and molecular scales?

[2] DOE (U.S. Department of Energy), Carbon Sequestration Research and Development, DOE/SC/FE-1, Washington, D.C., 2000.

(3) **Assessment**: What ecosystems offer the best potential for enhanced sequestration? What potentially negative impacts exist?

(4) Implementation: How should one effectively manage ecosystems? What does it cost? What are the net impacts to greenhouse gas emissions?

Approach

The BER research approach involves supporting a diverse portfolio of projects directed at the research challenges in carbon sequestration. In addition, there are other programs within BER that are providing important complementary research results that have application to carbon sequestration. We summarize first some of the related programs and then give specifics within the Carbon Sequestration Research Program.

<u>Terrestrial Carbon Program (TCP)</u>

The Terrestrial Carbon Program (TCP) performs research that provides the scientific underpinnings for predicting future concentrations of CO_2 in the atmosphere. The research, which focuses on natural systems that regulate the abundance of CO_2 in the atmosphere, emphasizes (1) understanding the processes controlling the exchange rate of CO_2 between the atmosphere and the terrestrial biosphere; (2) developing process-based models of atmosphere-terrestrial carbon exchange; (3) evaluating source-sink mechanisms for atmospheric CO_2; and (4) improving the reliability of global carbon models for predicting future atmospheric concentrations of CO_2. Three particularly key parts of the TCP are (1) Mechanistic terrestrial carbon models for evaluating the role of the biosphere in atmospheric CO_2 changes, and the influence of climate and other feedbacks on the biogeochemical cycle of carbon, (2) AmeriFlux network of CO_2 measurements for estimating carbon cycling by terrestrial ecosystems, and (3) Free Air CO_2 Enrichments (FACE) experiments that evaluate the responses of terrestrial plants and ecosystems to increased concentrations of atmospheric CO_2.

AmeriFlux is of particular relevance as it involves the measurement of net CO_2 exchange of representative ecosystems across the United States and North America. Net annual CO_2 exchange is measured by eddy covariance methods producing annual estimates of net carbon gain or loss by ecosystems such as forests, grasslands and croplands. In addition to flux measurements, biological/ecological data are collected on processes such as photosynthesis, respiration, primary productivity and growth rates and the turnover of different ecosystem carbon pools. Together with flux measurements these data provide unique estimates of net ecosystem production (NEP); positive values of NEP mean the system is storing carbon and negative values indicate net loss of carbon. Initial results show that forest ecosystems are gaining carbon at the rate of 2 to 6 tons of carbon per hectare per year. This network of flux measurements, and related ecosystem and micrometeorological data collectively provide vital ground surface information about the carbon cycle and its relationship to carbon sequestration.

<u>Integrated assessment (IA)</u>

Integrated assessment (IA) of global climate change is the analysis of climate change from the cause, such as greenhouse gas emissions, through impacts, such as changed energy requirements for space conditioning due to temperature changes. Integrated assessment emphasizes feedbacks and is often, but not always, implemented as a computer model. BER research supports the development of fundamental information or methodologies rather than the exercise of a model to evaluate specific policy options. Key areas of study include: (1) Predicting the rate of technology innovation and diffusion, especially related to carbon emissions, (2) Representing non-CO_2 greenhouse gases, and (3) Representing carbon sinks and land use changes. Recently, a fourth area of emphasis has been added – representing carbon sequestration technology options.

Carbon Sequestration Research Program – Current Progress

BER research in carbon sequestration is approached in two ways. First, through a research consortium – known as CSiTE. Second, BER has recently funded a suite of individual investigator research projects that focus on specific scientific questions and candidate implementation approaches. Together CSiTE and the suite of projects address Carbon Sequestration Program objectives. This two-pronged approach allows mission-oriented research to progress by utilizing focused research teams complemented by individual-based research.

Center for Research on *Enhancing* Carbon Sequestration in Terrestrial Ecosystems (CSiTE)

CSiTE performs fundamental research to discover and characterize links between critical pathways and mechanisms for creating larger, longer-lasting carbon pools in terrestrial ecosystems. Research is designed to establish the scientific basis for enhancing carbon capture and long-term sequestration in terrestrial ecosystems by developing (1) scientific understanding of carbon capture and sequestration mechanisms in terrestrial ecosystems across multiple scales from the molecular to the landscape, (2) conceptual and simulation models for extrapolation of process understanding across spatial and temporal scales, (3) estimates of national carbon sequestration potential, and (4) assessments of environmental impacts and economic implications of carbon sequestration. CSiTE research is focused on two parallel and intertwined set of tasks. Figure 1 illustrates the multiple scale research and assessment activities. What is unique within CSiTE is the direct interaction and exchange of new science among scientists of different expertise ranging from chemists to microbiologist to ecologists to economists. During the first 18 months of research, field studies have been established in forests, grasslands, agricultural systems, and degraded lands. In addition, methods for estimating the net impact on greenhouse gas emissions via direct management for carbon sequestration have been developed. Models to assess both environmental and economic impacts resulting from energy-driven land management are being developed, improved and tested. A list of publications resulting from CSiTE research is available at: csite.esd.ornl.gov.

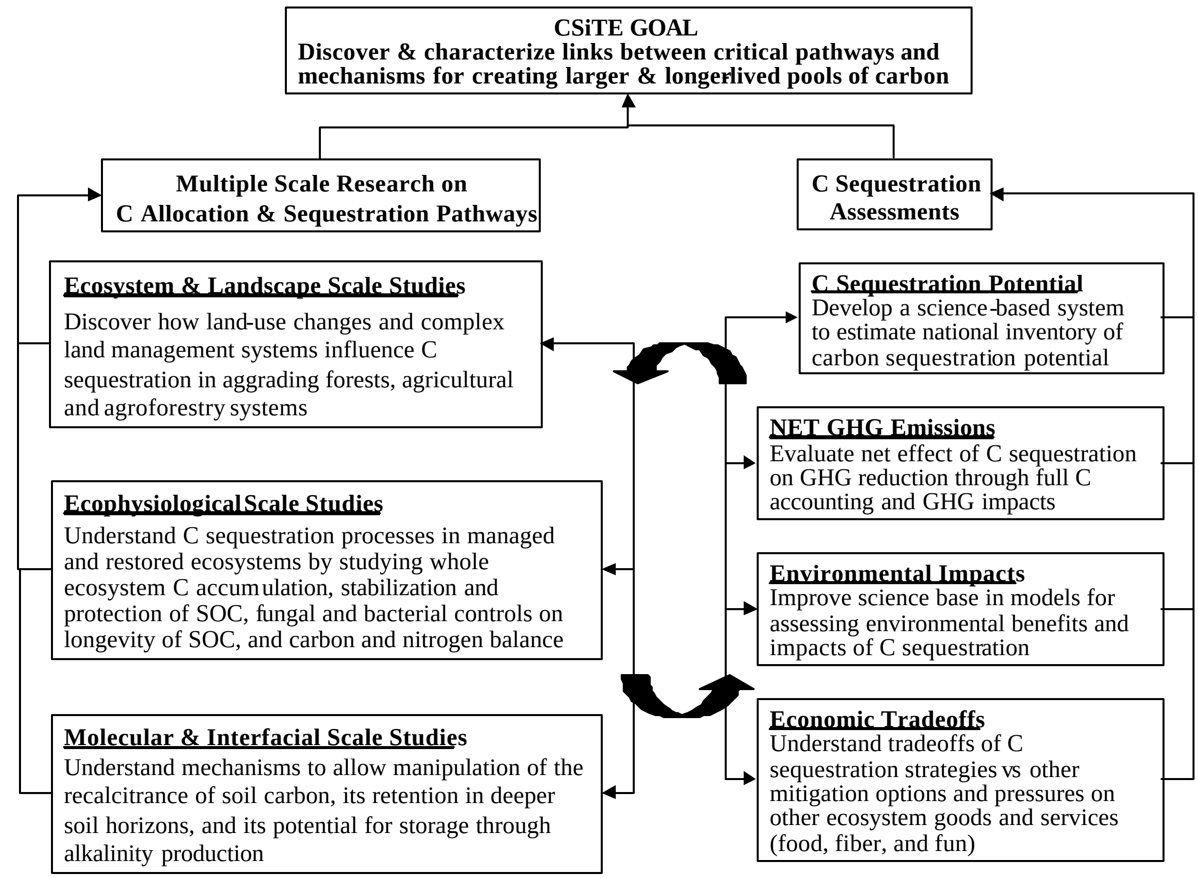

Figure 1. CSiTE consists fundamental research across multiple scales to elucidate possible ways to enhance the storage of carbon in ecosystems. In parallel, research into ways to assess the impacts of carbon sequestration methods is being accomplished. Information and data from the two tasks are shared by the CSiTE consortium resulting in direct feedbacks related to feasibility.

Carbon Sequestration Research Projects

The four objectives discussed earlier require a diverse portfolio of research. In the past year, several new projects were awarded by BER through competitive solicitation. These new projects span the four research challenges of the DOE roadmap. Although too new for significant research results to be available (however, some of these projects are being presented at this conference), a brief description of each will illustrate the depth of the science being covered.

1. Understanding of Carbon Sequestration

Soil Carbon Saturation: Determining Rates and Limits of Carbon Sequestration (PI: Johan W. Six, Colorado State University)

This project provides an experimental and theoretical framework to determine the saturation limits of different soils, the controls on those saturation limits, and their influence on the kinetics of soil C turnover and stabilization relative to C sequestration. The role of physiochemical soil characteristics in determining and constraining C sequestration rates and to quantify soil C saturation levels will be determined by integrating field sampling, laboratory analyses, and mathematical modeling to investigate how climate, soil texture, base saturation, input rates, input quality, and management interact to affect each of the four soil C pools.

Genetic and Environmental Controls on Carbon Allocation and Partitioning in Woody Plants – Implications for Ecosystem Carbon Sequestration
(PI: Stan D. Wullschleger and Jerry A. Tuskan, Oak Ridge National Laboratory)
The study will address aspects of carbon sequestration related to securely storing carbon in chemical forms that are resistant to microbial degradation and allocating carbon preferentially to roots where it can better contribute to soil carbon sequestration. The research will take advantage of a genetically well-characterized population of hybrid poplars growing in the Pacific Northwest. For every individual in this population, the chemical composition of leaves and roots, and the fraction of total carbon allocated to roots, will be determined. These traits will be compared against a genetic map that is being established for hybrid popular and genes important to carbon sequestration will be identified.

Mechanics of Soil Carbon Sequestration by Nitrogen Deposition
(PI: R.L. Sinsabaugh, University of Toledo)
The purpose of this project is to resolve the mechanisms that link N deposition with soil organic matter production and to assess the potential of this approach for manipulating carbon storage. The fieldwork will be conducted at nine well-characterized sites across Michigan that represent the major classes of northern temperate forest. The specific objectives are to measure the efficiency of decomposition (using enzyme turnover activities) in relation to carbon quality, N deposition rate, and microbial community composition (using phospholipid fatty acid analysis).

Quantifying the importance of belowground plant allocation for sequestration of C in soils
(PI: Margaret S. Torn, Lawrence Berkeley National Laboratory)
This project will investigate the efficacy of sequestration through belowground plant allocation by: (1) Quantifying the stocks and lifetime of live fine and coarse roots; (2) Determining the lower bound of NPP "pumped" into soil carbon through these roots; (3) Comparing leaf and root decomposition including rates, microbial communities and humification products; (4) Characterizing the turnover times of soil organic matter pools, and (5) Tracking the partitioning of recent plant photosynthate to rapidly lost root respiration and exudate mineralization, and more slowly lost root tissues and soil organic matter.

<u>2. Measurement of Carbon Sequestration</u>

In-Situ Non-Invasive Soil Carbon Measurement
(PI : Lucian Wielopolski, Brookhaven National Laboratory)
This project will develop a robust, flexible, non-invasive, and practical method for monitoring and verifying temporal changes in soil carbon *in situ*. The method is based on Inelastic Neutron Scattering (INS) of fast neutrons from the carbon nucleus and detection of the subsequently emitted 4.4 MeV gamma rays. The two major objectives of this project are to: (1) construct a prototype of a field deployable Soil Carbon Measurements (SCM) system, and (2) characterize, calibrate and test the SCM system in the Free-Air CO_2 Enrichment (FACE) facility at the Duke

Forest, NC, where laboratory carbon measurements of soil core samples are currently in progress.

Field-Portable Spectroscopy Measurements of In Situ Soil Carbon: Inventories, Spatial Heterogeneity, and Dynamics in Semiarid Environment
(PI: David D. Breshears, Los Alamos National Laboratory).
This project will use emerging technology for soil carbon measurement to assess the potential for semi-arid ecosystem to provide low-cost sequestration options. The research (1) utilize two proven spectroscopic technologies to develop an integrated instrument for field use;
(2) demonstrate this instrument by measuring carbon inventories through time in semiarid field sites; and (3) use this instrument to measure changes in soil carbon at sites in response to carbon sequestration practices and/or climate. The spectroscopic technologies to be applied are laser-induced breakdown spectroscopy (LIBS) to measure total soil carbon, and Raman spectroscopy, to differentiate organic and inorganic soil carbon.

3. Assessment of Carbon Sequestration
Economically Viable Forest Harvesting Practices That Increase Carbon Sequestration
(PI: Eric A. Davidson and Neal Scott The Woods Hole Research Center)
The objective of the proposed project is to determine whether shelterwood cutting regimes now being adopted in the commercial forests of Maine and other areas can achieve multiple goals. The carbon sequestration consequences of these shelterwood cuts in a typical northeastern commercial forest will be evaluated through intensive field measurements and integrative modeling. Whole-ecosystem C exchange will be measured in harvested and nearby unharvested mature spruce forests via micrometeorological and mensuration methodologies. It is hypothesized that shelterwood management will increase the net sequestration of C (onsite plus offsite) compared to a stand that is not being optimally managed for timber productivity.

4. Implementation of Carbon Sequestration
Pasture Management Strategies for Sequestering Soil Carbon
(PI: Alan J. Franzluebbers, U.S. Department of Agriculture)
This project seeks to integrate the measurement of soil organic carbon (SOC) sequestration in Eastern pasture management systems with soil quality, water quality, and animal performance and productivity in a unique combination of replicated water catchments with diverse plant genetic resources. Sequestration of C in soils under pastures has great potential to offset a portion of the annual greenhouse gas emissions in the USA, because (1) pastures constitute a major land use, (2) fixation of atmospheric CO_2 by pasture plants occurs throughout a great portion of the year, (3) decomposition of organic materials in pastures is slowed by limited water due to rapid plant utilization, and (4) a large root biomass and return of feces to land provide continuous C inputs. The rate and magnitude of SOC accumulation will be determined under three important management variables that producers have control over: (1) plant genetic source, (2) poultry litter versus inorganic fertilizer application, and (3) grazing of cattle versus haying.

Carbon Sequestration in Dryland and Irrigated Agroecosytems: Quantification at Different Scales for Improved Prediction
(PI: Shashi Verma, University of Nebraska)
This research will investigate carbon sequestration within three major agroecosystems (a rainfed maize-soybean rotation, an irrigated maize-soybean rotation, and an irrigated continuous maize system). Tasks to be emphasized include: (a) quantifying annual amounts of C sequestered and the associated interannual variability, at the landscape level, employing eddy covariance flux systems year-round, (b) quantifying soil C changes using georeferenced soil samples, and (c) developing reliable, cost-effective procedures for predicting annual C sequestration and changes in soil C stocks at the scale of a single production field using detailed crop yield mapping. Importantly, the work will also quantify "C costs" of applied energy-dependent inputs (e.g., N fertilizer, irrigation, grain drying), and changes in N_2O and CH_4 emissions and integrate these results into net C sequestration values.

Benefits and Applications
The DOE roadmap for carbon sequestration sets goals of having the understanding and technology ready for implementation of significant carbon sequestration options by 2025. The BER research portfolio described in this paper represents initial investments for advancing the science and technology of carbon sequestration in terrestrial ecosystems. These initial priorities were selected based on the needs as outlined in the DOE roadmap. The research challenges are significant and collaborations with programs in other agencies are an important part of the overall DOE strategy. The science of sequestration is still young and new approaches to the research are likely to evolve rapidly from these initial steps, leading to a sound scientific basis for cost-effective and viable options for long-term storage of carbon to help mitigate increasing atmospheric CO_2 concentrations.